Acoustic Sensing with Capacitive Micromachined Membranes and Radio Frequency Detection

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ABSTRACT

Broadband acoustic sensing over several decades of frequency has traditionally been difficult to achieve. Conventional condenser and electret microphones typically depend on membrane or cavity resonances to achieve their maximum sensitivity, which inherently limits the frequency range of the acoustic sensor. In addition, the large, thin diaphragms typically used to sense low-frequency sound are extremely fragile and are not suited for hostile outdoor environments as might be encountered on the battlefield.

New microphones using capacitive micromachined ultrasonic transducer (CMUT) technology and radio frequency (RF) detection overcome many of the problems associated with conventional microphones. These micromachined membranes are small and robust enough that they can be vacuum-sealed and still withstand atmospheric pressure and submersion in water. The sealing process not only seals out moisture, but also suppresses the mechanical noise associated with squeeze-film damping of air behind the membrane. Because the ultrasonic membrane's resonance is well above the frequencies of interest, the membrane mechanical response is very flat from DC up to several hundred kilohertz. Although the mechanical signal-to-noise ratio is very high, the changes in membrane capacitance are very small, so a sensitive RF detection scheme is necessary to recover the acoustic signal.

In this paper, we present the theory and modeling of RF detection with CMUT membranes. Previous experimental results already demonstrate the flat frequency response of the acoustic sensor, with responses varying only 1 dB over a range of 0.1 Hz to 100 kHz. Several strategies, most notably for reducing transmission line loss, are described to improve the sensitivity of the microphone from its measured value of 53 dB/Pa/Hz on recent devices. With the improvements, simulation results predict that device sensitivities greater than 100 dB/Pa/Hz are possible with a device that is only 4mm in size.

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Abstract

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1. Introduction

1.1. Motivation and Objectives

The demand for sensitive microphones, coupled with advancements in micromachining technology has led to the development of many miniature acoustical pressure sensors. Most of these microphones are based on a capacitive or condenser design, with one or more micromachined membranes responding to acoustic pressure. To date, most of the development of miniature microphones has focused on hearing aid applications that are designed for detection of frequencies of several tens of hertz to 20 kHz [1].

Many industrial and military applications require acoustic data collection over larger bandwidths for proper signal identification. Acoustic emissions upwards of 100 kHz, due to very short bursts of sound, can be analyzed for condition monitoring of equipment [2]. At these high frequencies, accurate detection is best achieved with a small sensor to limit the effects of diffraction [3]. In addition, low frequency detection below the audio range is useful for monitoring acoustic signals from various engines and heavy equipment [4]. Unfortunately, sensitive detection of low-frequency sound is best achieved with very large, fragile diaphragms, which might not be robust enough for many applications in the field. For operation in environments such as the battlefield, a sensor should also be insulated from dust and water, and it should be capable of withstanding large accelerations or shocks. This paper describes theory, experimental results, and strategies for improving the design of a robust, miniature microphone for measuring broadband acoustic signals near DC up to 100 kHz.

1.2. Capacitive Microphones

Capacitive microphones or transducers consist of one or more conductive diaphragms suspended over a conductive backplate [5]. Sound detection is possible when the impinging pressure vibrates the diaphragm, thus changing the capacitance of the transducer. For conventional microphones, the change in capacitance is detected by measuring either the output current under constant-voltage bias or the output voltage under a constant-charge on the diaphragm electrode. Fig. 1 shows such a constant-voltage bias circuit, where the transducer is represented as a variable capacitor.

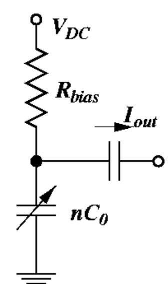

Fig. 1. Constant-voltage bias circuit for a capacitive transducer.

The trend in capacitive microphone technology has been to make the diaphragm as thin and as large as possible for detection of low-frequency signals. The gap between the diaphragm and backplate is kept as small as possible for the maximum change in capacitance for diaphragm displacement. Unfortunately, such a structure suffers from squeeze-film effects, non-linearities, and durability issues. Most importantly, traditional capacitive microphone technology depends on mechanical resonance phenomena to achieve maximum sensitivity, though only over a limited frequency range.

Recently, a new type of capacitive transducer has been developed, largely for ultrasound applications in

air and water. The capacitive micromachined ultrasonic transducer (CMUT) consists of hundreds or thousands of rectangular or circular silicon-nitride (Si_xN_y) membranes electrically connected in parallel to form a capacitor [6]. This device behaves similarly to the conventional condenser microphone, except for its dimensions and different range of applications. As depicted in Fig. 2, CMUTs for use in air applications typically have a membrane thickness of approximately 1 μm and membrane width or diamater of around 90 μm, with dimensions accurately controlled by lithography and semiconductor fabrication technology [7]. These membranes can be vacuum-sealed; that is, the area beneath the membrane can be evacuated during fabrication. This seals out moisture and particles which otherwise might affect or restrict the membrane's movement, while also eliminating squeeze-film effects. In addition, a protective material such as low-temperature oxide can be deposited over the aluminum metalization for operation in or around water. The above device geometry results in a structure that resonates at 2-3 MHz, and is therefore useful for ultrasound applications in air or immersed in water [6]. However, such devices are narrow-band when operating in a low-impedance medium such as air.

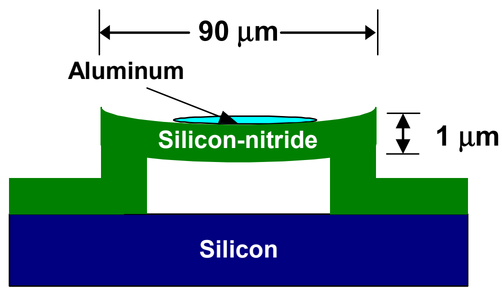

Fig. 2. Constant-voltage bias circuit for a capacitive transducer.

2. Capacitive Membranes with Radio Frequency Detection

2.1. Membrane Geometry for Flat Frequency Response

In an effort to broaden the frequency response of microphones, an alternative approach to microphone design is proposed. Instead of large, thin membranes with air-backing as in traditional microphones, we propose fabricating many small CMUT membranes with thicker, more robust diaphragms than usual. With smaller membranes, the cavity behind these membranes may be vacuum-sealed during processing, and the membrane can still withstand atmospheric (or higher) pressure without collapsing to the substrate. Operation over a wide temperature range is expected since membranes survive processing steps of several hundred degrees Celsius. Because CMUT membranes resonate at a few megahertz, the displacement response of such membranes to pressure inputs is relatively constant up to several hundred kilohertz. This results in a sensor with a very flat frequency response below the membrane resonance. If the cavity behind the membrane is evacuated, pressure variations near zero frequency (atmospheric pressure fluctuations) may be sensed by measuring the change in capacitance.

To better understand the advantages and disadvantages of acoustic sensors, it is useful to express the usual definition of microphone sensitivity, the ratio between received voltage and input pressure, as a product of two terms: the mechanical sensitivity and the electrical sensitivity [5]. The mechanical sensitivity relates the membrane displacement to an incoming acoustic pressure while the electrical sensitivity relates the output voltage to the membrane displacement.

It is clear that utilizing small, stiff membranes below their resonant frequencies will drastically reduce the membrane displacement for a given input pressure. As shown in Fig. 3, the average membrane displacement for a membrane of typical dimensions is a fraction of an angstrom for a 1 Pa pressure input,

but very flat up to about 100 kHz. To obtain a reasonable overall sensitivity, this reduction in displacement sensitivity must be compensated with an extremely sensitive method of detecting slight changes in capacitance, without significant degradation of the signal-to-noise ratio. Radio frequency (RF) detection is an alternative detection method for sensing the slight changes in capacitance due to membrane movement.

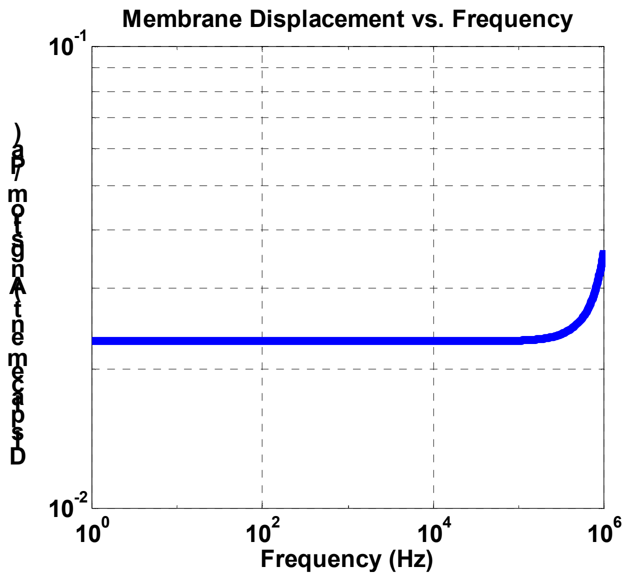

Fig. 3. Membrane displacement as a function of frequency for a typical CMUT membrane.

2.2. Overview of RF Detection Method

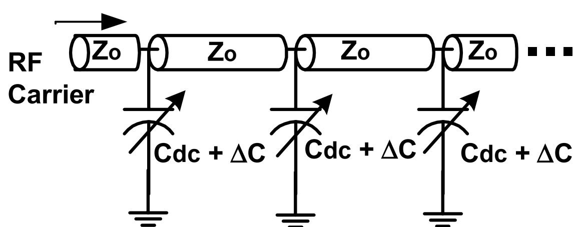

Fig. 4. A transmission line that is periodically loaded with capacitive membranes.

In RF detection, several hundred CMUT membranes are connected in series by short sections of transmission line, thereby creating a capacitively-loaded transmission line. The membranes form variable capacitors that are periodically spaced along the transmission line as shown in Fig. 4. As the capacitive membranes in the line vibrate due to incoming sound pressure, the propagation constant of the loaded transmission line also changes, effectively modulating the electrical length of the line. If a radio frequency (RF) carrier signal that is launched down the artificial transmission line is phase modulated by the acoustic signal [8]. Subsequent phase detection or demodulation yields the acoustic signal. The microphone itself operates in a phase detection circuit such as the one shown in Fig. 5. The output signal represents the acoustic pressure signal on the microphone.

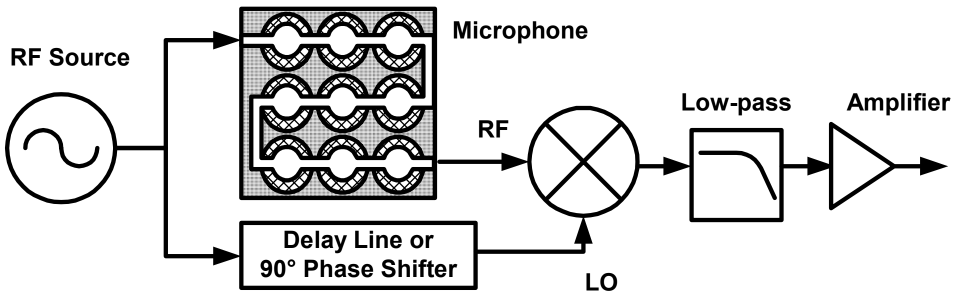

Fig. 5. The phase-detection circuit (with microphone) used in RF detection.

The electrical length of the transmission line in radians, as well as the phase modulation of the transmitted RF signal in radians/Pa, is proportional to the number of membranes and the frequency of the RF signal. Clearly, higher RF frequencies will boost the electrical sensitivity until transmission line loss, which also increases with frequency, affects the system's ability to detect the phase changes. By neglecting the conversion loss of the mixer and subsequent amplification stages, a simple approximation for the signal output of the mixer is possible:

$$I_{Out} = \frac{V_{RF}}{4} e^{-\alpha n} n C_0 \omega_{RF} \frac{\Delta x}{x_0}. \qquad (1)$$

In equation (1), n is the number of membranes or sections in the line, C_o is the capacitance of single membrane, x_o is the initial separation between capacitor electrodes, Δx is the membrane's amplitude of vibration, V_{RF} is the RF voltage, α is the attenuation constant per section in nepers, and ω_{RF} is the RF radian frequency [8].

Some of the benefits of RF detection are evident through this simplified equation. Most importantly, the output current in RF detection is directly proportional to the RF frequency. If the RF frequency is several gigahertz, the electrical sensitivity of the RF detection method can be many orders of magnitude larger than that of the constant-voltage detection or constant-current detection methods [9]. Furthermore, the output signal in RF detection is independent of the acoustic signal, as long as the amplitude of vibration is frequency-independent, as it has been shown to be in Fig. 3. Thus, RF detection on vacuum-sealed devices permits sensing of arbitrarily low-frequency pressure fluctuations, within the limits of 1/f noise.

3. SNR as a Measure of Sensitivity

3.1. Mechanical Noise

As mentioned earlier, microphone sensitivity is traditionally described in terms of output voltage response for an input pressure. This information alone will not completely describe the performance of the microphone unless accompanied by figures describing the noise performance of the microphone. Therefore, in this paper we commonly use the signal-to-noise-ratio of the system as a measure of the microphone sensitivity in an electrical system, often quoted in decibels (dB) relative to a 1 Pa pressure input. Very often, the mechanical noise of condenser microphone limits the performance of the sensor, regardless of the quality of the amplifying electronics.

As can be seen from a microphone design using RF detection, the mechanical sensitivity in terms of displacement for input pressure is drastically reduced. However, the mechanical SNR is improved with

vacuum-sealing of the devices because the mechanical loss mechanisms, which are responsible for the noise in the system, are minimized. Squeeze-film damping due to air behind the membrane in unsealed membrane devices is the dominant noise mechanism for most well-designed condenser microphone designs [10]. By eliminating the major source of acoustical resistance, vacuum-sealed CMUT membranes have a much lower mechanical noise floor. Calculations indicate that mechanical noise in sealed CMUT membranes is small enough to be neglected in most analyses [9]. Instead electrical noise plays a more important role in limiting device performance.

3.2. Electrical Noise

There are several sources of electrical noise in the system. First, there is the thermal noise power on the transmission line given by kT_o in a 1 Hz bandwidth, where k is Boltzmann's constant (1.38 x 10 J/K) and T_o is the absolute temperature of the system. The amount of noise power on the transmission line will be independent of the loss of the line as long as the system is in thermal equilibrium [11]. The quadrature component of this thermal noise is mixed to baseband and again has value kT_o in a 1 Hz bandwidth [12]. Furthermore, the mixer introduces its own thermal noise due to the conversion loss between the RF port and the intermediate frequency (IF) port. Subsequent amplification of the baseband signal also introduces additional thermal noise into the system.

3.3. Signal Calculation Methods

There are several stages to calculating the output signal and noise levels for a CMUT microphone with RF detection. First, the static (DC) deflection of the membrane under atmospheric pressure is calculated using plate equations for a stretched diaphragm with thickness and tensile stress [13]. Transmission line phase velocities and attenuation are also calculated for a section of unloaded transmission [14]. Next the capacitance due to a single membrane cell is calculated, accounting for the deflection of the membrane due to atmospheric pressure. This capacitance is used to load the section of transmission line. Lumped parameter approximations, which are valid up to several tens of gigahertz, are used to calculate the propagation constant and attenuation of the capacitively loaded transmission line [15]. The same calculation is repeated for a membrane that is subjected to a low-frequency acoustic pressure superimposed on the static DC pressure. The amount of phase shift per section due to the acoustic signal is found from the difference in the propagation constants of the two sections of line. Multiplying the phase shift per section by the number of sections gives the total phase shift of the line. The signal power at the output of the phase detector is given by the product of the RF power (after losses) and the square of the total phase shift in radians.

4. Experimental Results

4.1. Measurements

In the absence of elaborate acoustic measurement equipment, acoustic performance in initial devices is evaluated by vibrating the membranes electrostatically with an applied voltage. The actual displacement of the membrane under this electrostatic actuation is measured using an optical interferometer. Analysis of the output signal permits measurement of the electrical sensitivity of the RF detection method. By calculating the equivalent pressure input that results in the same applied displacement, a measurement of the overall sensitivity of the microphone system is possible.

The microphone consists of 258 rectangular membranes periodically loading a microstrip line at distances of 114 μm. The membrane thickness is 1.3 μm and has dimensions of 100 μm x 800 μm, suspended 1 μm above the substrate. The area of the device is approximately 4 mm x 4 mm. With an RF frequency of

113 MHz, the SNR at 10 kHz is 82 dB/Hz for a measured membrane displacement of 7.5 Angstroms. This suggests that the minimum detectable displacement using this RF detection configuration is $6.4 \cdot 10^{-4}$ Å/√Hz.

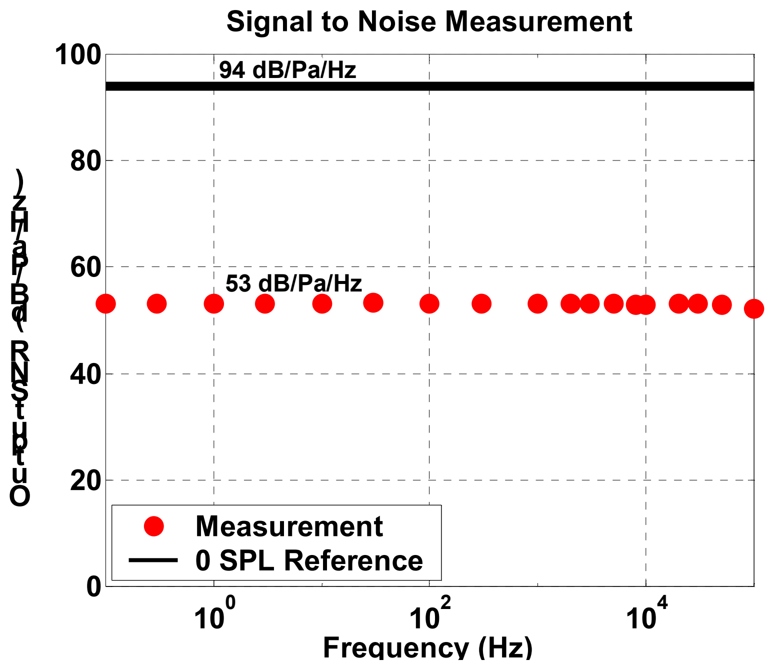

Fig. 6. Measured output SNR (dB) relative to 1 Pa equivalent input pressure, compared to reference level of 0 SPL for the human ear. The frequency ranges from 0.1 Hz to 100 kHz.

Collecting signal outputs at a variety of frequencies demonstrates the relatively flat frequency response that is possible with RF detection and CMUTs. Fig. 6 shows the microphone's SNR based on the equivalent acoustic pressure input from 0.1 Hz to 300 kHz. This is compared to the commonly accepted reference of 0 sound pressure level (SPL) for the human ear, which is equivalent to 94 dB SNR relative to 1 Pa. The sensitivity of the microphone over the frequency range is 53 dB/Pa/Hz ± 1dB.

4.2. Discussion of Results

The device tested in the results of Fig. 6 was designed for conventional ultrasonic applications, and therefore was not optimized for use with RF detection in terms of membrane geometry or for reduction of RF loss on the connecting microstrip transmission line. In fact, a relatively low RF frequency of 113 MHz was used in these experiments because the RF loss was prohibitively large at higher frequencies. For the device tested, which is 3 cm in length, the transmission line loss at 100 MHz is 14 dB, and increases to 44 dB at 1 GHz. This transmission line loss reduces the output signal level and overall SNR proportionally. In addition, high transmission line loss prevents the use of higher RF frequencies, which could further increase the signal level.

4.3. Strategies for Improving Sensitivity

The greatest improvement to the microphone sensitivity is possible by reducing the high levels of transmission line loss in the devices. A coplanar waveguide (CPW) transmission line geometry reduces the conduction loss of the line since it permits wider signal lines without while maintaining a high characteristic impedance [14]. Loss can be further decreased by burying the transmission lines

underneath the membrane, which permits arbitrarily thick metal lines without adversely affecting the CMUT membrane movement. Based on other literature results, we expect that transmission lines with less than 0.4 dB/cm loss at 1 GHz can be fabricated on high resistivity silicon substrates [16]. For the device measured in Fig. 6, the expected SNR with such a low-loss line and an RF frequency of 1 GHz is 90 dB/Pa/Hz.

Improvements to the phase detection circuit can further improve the sensitivity of the RF microphone. Insertion of a low-noise RF amplifier before the mixer in the phase detection circuit Fig. 5 compensates for some of the loss of the RF microphone's transmission lines, thus permitting longer transmission lines in the RF microphone for more phase modulation. Because many commercially available RF amplifiers have noise figures below 1 dB, the usually poor noise performance of the mixer is discounted by the gain of this amplifier. This simple modification to the detection circuit, coupled with low-loss transmission lines could yield an SNR above 100 dB/Pa/Hz.

5. Conclusion

The RF detection method discussed in this paper is a very sensitive method for detecting displacement. When combined with sealed CMUT membranes, a microphone with very broad, yet flat, frequency response is possible. Initial experimental results of a microphone using RF detection demonstrate a sensitivity of 53 dB/Pa/Hz. Large improvements to the output SNR, perhaps more than 40 dB, can be obtained by reducing the RF loss of the transmission lines and increasing the RF frequency. Further optimization of membrane geometry with improvements to the phase detection circuitry should permit RF microphones to achieve sensitivities nearing 100 dB/Pa/Hz, or the ability to sense pressures as low as 10 μPa/Hz over a wide acoustic bandwidth. The resulting device will be only a few millimeters in size, yet robust enough to operate and withstand dust, moisture, and extremes in temperature, as might be encountered in a military environment.

6. Acknowledgment

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